British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

The International Geomagnetic Reference Field (IGRF) generation 12: BGS candidates and final models

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The International Geomagnetic Reference Field (IGRF) model is a reference main field magnetic model updated on a quinquennial basis. The latest revision (generation 12) was released in January 2015.

The IGRF-12 consists of a definitive model (DGRF2010) of the main field for 2010.0, a model for the field at 2015.0 (IGRF2015) and a prediction of secular variation (IGRF-12 SV) for the forthcoming five years until 2020.0. The remaining coefficients of IGRF-12 are unchanged from IGRF-11.

Nine candidates were submitted from various international teams for consideration to the IGRF Taskforce led by Erwan Thebault (Nantes) and Chris Finlay (DTU Space). The final models were computed from all candidates using a Huber weighting in space scheme.

In this poster, we outline the modelling steps for the three BGS candidate models and compare them to the other submitted candidates and the final official models released as IGRF-12.

BGS candidate models

The BGS submitted three candidates: a DGRF model for 2010.0, an IGRF model for 2015.0 and a secular variation prediction valid from 2015.0 to 2020.0. The main field models were constructed from SWARM, CHAMP and Oersted satellite data and from ground-based observatory data. The technical details are as follows [1]:

Satellite data

Data are selected over the following date ranges: Oersted: 2009.0 – 2013.5; CHAMP (calibration level version 51): 2009.0 – 2010.7; Swarm Alpha, Beta, Gamma (revision 0301 & 0302): 2013.9 – 2014.7; Vector data are used at all latitudes. Scalar data are used only when vector data are unavailable.
Data within the above date ranges are further selected according to the following criteria: Kp now and over the previous 3 hours: |dDst/dt| < 5 nT/hour; 0 ≤ IMF Bz ≤ +6 nT; -3 ≤ IMF By ≤ +3 nT; -10 ≤ IMF Bx ≤ +10 nT; Solar wind speed ≤ 450 km/s; 22:30 ≤ local time (hour:min) ≤ 05:00 for -50° ≤geomagnetic latitude ≤ +50°; |(observed magnetic field) - (field from IGRF-11)| ≤ 700 nT; |F from scalar magnetometer) - (F from vector components)| ≤ 2 nT; Manual rejection of 'bad' Swarm data (11 days) using daily Quick-Look product produced by BGS for ESA. Data are sub-sampled to every 20th datum. But all data are used to calculate the along-track standard deviation over each 20 s data segment. This standard deviation is used to weight the data for each data source (CHAMP, Oersted, Swarm). Data variances were calculated from a combination of noise terms based on: (a) Along-track standard deviation calculated over every 20 s segment of data; (b) External field activity as measured at the geographically nearest magnetic observatories; (c) Spatially uniform noise (2 nT standard deviation) and (d) A function of solar zenith angle (in nT): 2*(1+cos(zenith))^2. These variances were then scaled by data density within 1-degree equal-area tesserae. High latitude data, though more numerous, have relatively low weight. No weighting was applied to achieve even temporal coverage.

Observatory data

Hourly mean observatory data were selected between 2009.0 and 2014.7. Data within the date range were further selected according to the following criteria: Kp ≤ 2+; |dDst/dt| ≤ 5 nT/hour; IMF Bz ≥ -2 nT; 01:00 ≤ local time (hour:min) ≤ 02:00. The criteria resulted in selected data from 148 observatories across the globe. Data variances were calculated from a combination of noise terms based on: (a) Spatially uniform noise for vector data at mid-/low latitude (2 nT standard deviation); (b) Spatially uniform noise for pseudo-scalar data (see below) at high latitude (6 nT standard deviation) and (c) A function of solar zenith angle (in nT): 2*(1+cos(zenith))^2. A factor is applied to the variances of all data such that an approx. measure of total weight in model fitting is approx. 1/10th that of satellite data.
Pseudo-scalar data: above 60° geomagnetic latitude, vector data were projected along a priori main field estimates to make pseudo- scalar data that are linear in the Gauss coefficients to ease the solution of the crustal biases.

Parameterisation

The parameterisation of the parent model is as follows: Time-varying internal coefficients up to degree 13 using order 6 B-splines. Knots are at 1 year intervals, with five-fold knots at the endpoints of 2008.67 and 2014.67. This results in a total of 17 knots (5 interior, 11 exterior) and 11 B-spline functions; Static internal coefficients from degree 14 to 55. Degree 1 external field with time dependence by: a piecewise linear function with knots at ¼ year intervals, Vector Magnetic Disturbance index dependence, and 24 hour, annual, and semi-annual periodicities; Biases are fit individually at each observatory to account for static localised anomalies.

Model fitting

The model parameters are fit using a regularised minimum norm approach, applying damping to the time-varying internal coefficients to find smooth models which fit the data using an L2 norm. Two types of temporal damping are employed: the first constrains the rate of change of the radial magnetic field at the core surface, by using a block diagonal regularisation matrix that minimises the squared magnitude of the second time derivative; the second damping term uses a block diagonal regularisation matrix that minimises the squared magnitude of the third time derivative of the radial field at Earth's surface (a sphere with radius 6371.2km).

Extraction/extrapolation of 2010, 2015, and SV models

From the parent model, the final internal coefficients are extracted as regular snapshots between 2009.0 and 2014.5. The internal coefficients to degree 13 are extracted at 2010.0 for the DGRF. The snapshots are then used to construct a steady core flow and acceleration model up to degree 13. The SV and SA coefficients from the core flow and acceleration model are used to advect the flow forward from 2014.5 to 2015.0 from which the magnetic field is extracted up to degree 13 for the IGRF-12 model at 2015.0. The core flow and field are then further advected forward in time from 2015.0 to 2020.0. The difference between the magnetic field in 2020.0 and 2015.0 is used to provide secular variation coefficients to degree 8 and degree 13.

Figure 1 shows the quantity and geographic distribution of the satellite and ground observatory datasets used in the production of the models.

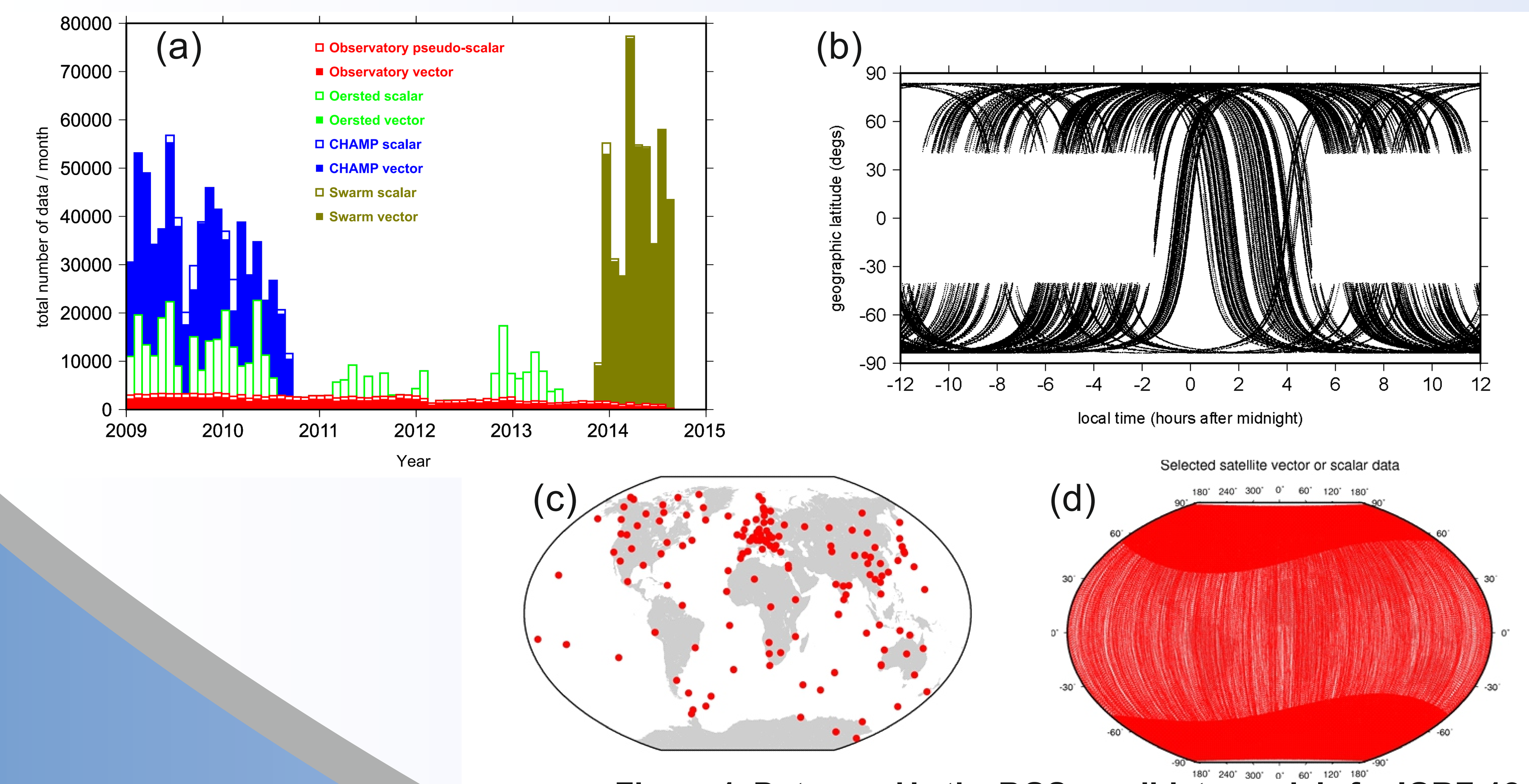

Figure 1: Data used in the BGS candidate models for IGRF-12.
(a) Histogram of number and type of data with time.
(b) Example of geographic versus local time selection of Oersted satellite scalar data.
(c) Location of 148 ground-based observatories.
(d) Total geographic coverage for Swarm satellite data.

IGRF-12 candidates and final models

There was an excellent response to the for candidates for the new release of the IGRF series. The models were independently tested and assessed by the Taskforce. See [2] for further details and reports. Many of the same techniques described in [3] were used to assess the quality of each candidate.

DGRF2010: Seven candidate models were submitted for DGRF2010. All were very close to each other, in RMS difference, though there was some variation between teams. Figure 2 (left panels) shows the Lowes-Mauersberger spectra and RMS differences between each of the candidates and the final model.

IGRF-12: Nine candidates were submitted for the IGRF2015 model. There was a wider scatter than for the DGRF2010 model due to extrapolation to 2015.0 and the differing modelling approaches adopted. Figure 2 (centre panels) show the spectra and RMS differences between each of the candidates and final model.

IGRF-12 SV: There were nine candidate submissions for the secular variation prediction for the five years between 2015.0 and 2020.0. These models showed the greatest variation due to the different and innovative techniques used by the various teams. Figure 2 (right panels) show the spectra and RMS differences between each of the candidates and the final model.

The final models were generated using a Huber weighting scheme in space (i.e. not Gauss coefficients). Thus all candidates contribute to the final official IGRF-12 models.

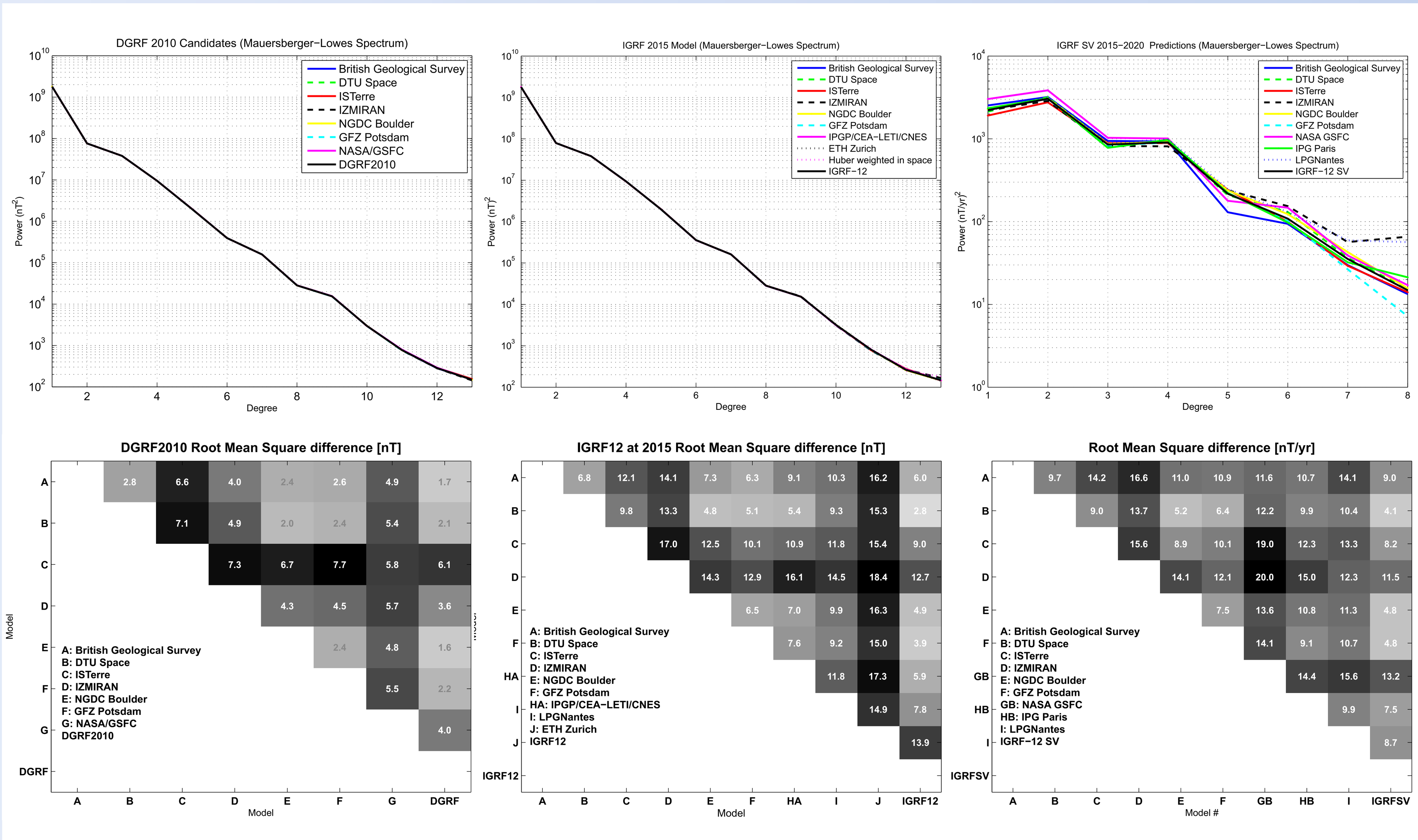

Figure 2: Power spectra and RMS differences between the candidates and final models of (left) DGRF2010, (centre) IGRF2015 and (right) IGRF-12 SV.

Discussion

The seven candidates submitted for the DGRF2010 were within a few nT RMS difference of the final model. This is due to the use of CHAMP data around 2010 to constrain the field. For the IGRF2015 model, there was slightly greater variation due to extrapolation to 2015.0. In addition several teams used different techniques to estimate the various contributions to the main field from external sources. The SV candidates had the largest variation between teams. Some teams opted for mathematical extrapolation, while others used core flow or geodynamo modelling to estimate the linear variation of the field over the next five years.

The final models are created using Huber weighting in space to blend together all of the candidates in a robust manner. Further details will be given in the Special Issue of *Earth Planets and Space* due for publication in 2015. Figure 3 shows the final IGRF-12 model for 2015.0 and the SV estimate for the five years from 2015.0 to 2020.0.

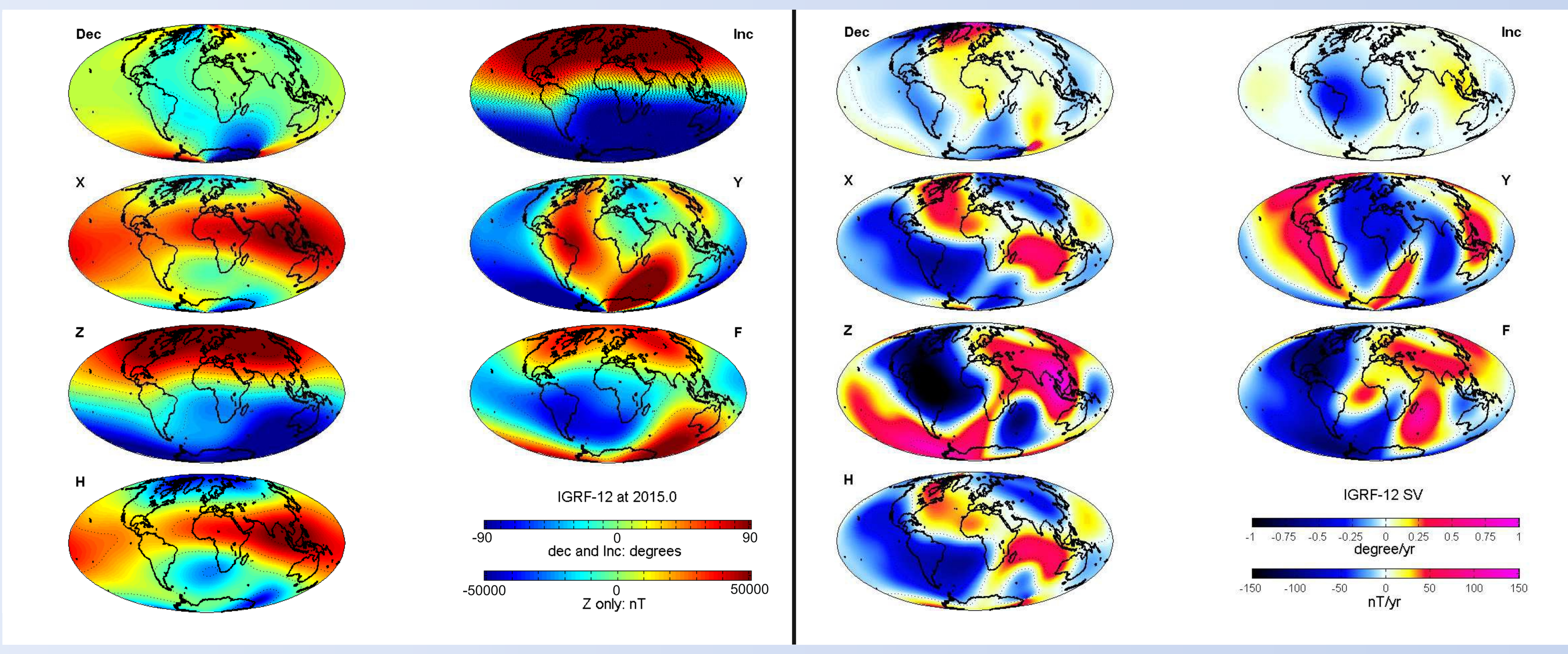

Figure 3: (left) The IGRF-12 main field model at 2015.0 and (right) the average secular variation estimate for 2015.0 to 2020.0.

References

[1] Hamilton, B., V. Ridley, S. Macmillan, A. W. P. Thomson and C. D. Beggan (2015), The BGS magnetic field candidate models for the 12th generation IGRF. Earth, Planets and Space, *in preparation*
[2] See: http://www.sciences.univ-nantes.fr/lpgnantes/static/igrf-12/ for details and reports on the candidates and the evaluations
[3] Finlay, C. C., S. Maus, C. D. Beggan, M. Hamoudi, F. J. Lowes, Nils Olsen, and E. Thébault (2010), Evaluation of candidate geomagnetic field models for IGRF-11. Earth Planets and Space 62, 787-804

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http://www.geomag.bgs.ac.uk/data_service/models_compass/igrf.html

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